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Greenhouse gas emissions associated with electric vehicle charging: The impact of electricity generation mix in a developing country

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ABSTRACT

Since 2012, the government has been promoting the electric vehicles and the development of related infrastructure to encourage local automakers to explore into the alternatively powered vehicles. However, the benefits of grid-dependent EVs can only be harvested under the condition that their use is coupled with a low carbon electricity grid. Thus, it is an additional challenge for Malaysia's that are largely dependent on fossil fuels for electricity generation. The object of this paper is to perform a well-to-wheel life cycle assessment for calculating the greenhouse gas emissions attributable to the usage of ICEVs, HEVs and EVs in Malaysian scenario. These emission calculations will provide the best information for policymakers, researchers, and investors to make appropriate and effective decisions on policies, research and investments in future transport energy. The results show that running EVs with national grid will produce an average of 7% more GHG emissions than HEVs at the same distance. However, they will produce an average of 19% less GHG emissions than the ICEVs. Overall the GHG emissions produced through the usage of EVs are substantial based on the well-to-wheel analysis, as the environmental profile of EVs is linked with the national grid. Therefore, in order to harvest the benefit of EVs towards climate change and global warming mitigation, massive modernization and transformation should be taken for the development of the national grid towards greener sources.
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1. Introductions

The global electric vehicle volume on the road reached 1.26 million in 2015, where there were only half of them in a year before and hundreds in 2005. The Paris Declaration on Electro-Mobility and Climate Change and Call to Action sets a global deployment target of 100 million electric cars in 2030 (International Energy Agency, 2016). With each of the largest automakers globally offering one or more models every year, electric vehicle operations, and the magnitude of their environmental effects, are expected to bloom over time. Recent research report published by national automakers - Proton (Board of engineers Malaysia, 2012), shown that the conventional internal combustion engine vehicles (ICEVs) that travelled on a 1.5 l

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engine would produce approximately 180 g of CO_2 emission per kilometer, a hybrid petrol-electric vehicles (HEVs) with the same setting would produce 80 g of CO_2 emission per kilometer and electric vehicles (EVs) would produce zero tailpipe emissions. Since, EVs do not run on fossil fuels and have no tailpipe emission, there is a perception that EVs are an environmentally kind technology which emit lower Greenhouse Gases (GHG) (Delang and Cheng, 2012). However, the benefits of grid-dependent EVs can only be harvested under the condition that their use is coupled with a low carbon electricity grid (Hawkins et al., 2012; International Energy Agency, 2016; Ma et al., 2012). Thus, it is an additional challenge for Malaysia's that are largely dependent on fossil fuels for electricity generation. The national electricity generation is done with the combination of 52.2% of natural gas, 39.5% of coal, 5.1% of hydro power, 1.2% diesel oil, 1% biomass, 0.8% of fuel oil and 0.2% others (Table 1) (Energy Commission, 2010, 2012). Unlike the ICEVs, where their emissions from fuel usage are more or less similar over the same engine capacity, the EVs emissions from electricity usages could vary substantially from country to country and highly determined by the share and type of grid used to charge their battery (Table 1) (Energy Information Administration, 2012). Therefore, EVs of the same specification running in Japan or the US could generate different emission levels when they are operated on the Malaysian roads.

1.1. Problem statement

At the 21st United Nations Framework Convention on Climate Change (UNFCCC), in Paris, also known as the Paris Summit (COP-21), Malaysia pledged to cut the country's carbon emission intensity based on the Gross Domestic Product by up to 45% by 2030 relative to 2005 value, where 35% on an unconditional basis with a further 10% condition upon climate finance, technology transfer and capacity building (Goh, 2015). Ever since COP-15, Malaysia has taken numerous initiatives to reduce country's carbon emission through Malaysian Development Plan and policies, as in 2011, Malaysia's total carbon emissions represent about 0.6% of global emissions. The emission intensity per GDP was 0.41 tCO_2 eq/RM1000 for that year and it represents about 23% lower than 2005 values of 0.531 tCO_2 eq/RM1000 (Ministry of Natural Resources and Environment, 2015). The carbon emission from transportation sector has been one of the key sectors to be tackled as car ownership in Malaysia is the third highest in the world at a whopping 93 per cent with 54 per cent of households having more than one car (Faizli, 2016). Therefore, in line with the Malaysia's commitment, under the new revised National Automotive Policy (NAP), the government is promoting the hybrid and electric vehicles and the development of related infrastructure to encourage local automakers to explore into the alternatively powered vehicles (Ramanathan, 2013). However, with EVs, the local pollution may be reduced through tradeoff between the elimination of tailpipe emissions at the increase of emissions in the electricity production. Since, EVs would only move the emissions away from the road rather than reducing them globally, thus, it will bring more challenges and risks for policymakers and stakeholders to deal with the cost of emissions increase in the electric sector. (Hawkins et al., 2013). Thus, it is essential to conduct a detail environmental assessment on the usage of EVs, HEVs and ICEVs in order to calculate their potential greenhouse gas (GHG) emission.

1.2. Objective, scope and functional unit

The objective of this study is to calculate the potential GHG emission attributable to the usage of selected ICEVs, HEVs and EVs in Malaysian scenario using a well-to-wheel life cycle analysis. The scope of well-to-wheel assessment includes the life cycle analysis of petrol per litre, the life cycle analysis of the national electricity supply per kW h and the efficiency of vehicle (ICEVs, HEVs and EVs) based on vehicle test cycle. The vehicle test cycle from EPA and JC08 were adopted, therefore, no actual road test was carried out. Nevertheless, it produces lesser dissimilarity resulted from human errors during the driving phase of the vehicles. The functional unit used for this life cycle analysis is 100 kilometers (km) driven under the vehicle test cycle.

2. Method

The well-to-wheel analysis that was primarily motivated by the emergence of EVs is an LCA of vehicle fuels used to assess the fuel production pathway and vehicle fuel efficiency (Wang, 2003). It has been the crucial keys in assessing the environ-

Table 1
National electricity composition, 2010.

	Japan	United State	Malaysia
Coal	26%	45%	40%
Natural gas	27%	24%	52%
Nuclear power	27%	20%	–
Crude oil (diesel + fuel)	10%	1%	2%
Hydro power	7%	6%	5%
Renewable/biomass/solar	3%	4%	1%
Others		<1%	<1%

mental impact of fuel options as it explores the efficiency of the feedstock extraction, production, storage, transportation and distribution processes of the fuel, as well as the fuel efficiency in the vehicle (MacLean et al., 2011; Shena et al., 2012).

This research used SimaPro (PhD) software version 7.3.3 to perform the Life Cycle Assessment (LCA). LCA is the tool of choice used to compile, examine and evaluate the major flows of material and energy associated with the environmental performance of products, processes or services, throughout its entire life cycle (production, distribution, usage, maintenance and final disposal) (Onn and Yusoff, 2010). The Life Cycle Impact Assessment (LCIA) normalization method was performed using the hierarchical perspective (default model) of midpoint indicators of ReCiPe methodology. The ReCiPe uses an environmental mechanism as the basis for the modelling which transform and interpret the long list of Life Cycle Inventory into environmental impact indicator. The midpoint indicators were chosen because they are relatively more robust than the uncertain endpoint indicators (Goedkoop et al., 2013).

The Life Cycle Inventory (LCI) data from the Malaysia Life Cycle Inventory Database (MY-LCID) and Ecoinvent databases 2.2 were used. The LCI background data were obtained from the Malaysia Life Cycle Inventory Database (MYLCID) and used as the input data for the well-to-tank stage. However, the inventories obtained for fuel usage only covers until the refinery, in order to produce a well-to-wheels scenario, external process data from Ecoinvent databases were adapted. The dataset of Ecoinvent for "operation, passenger car, petrol, fleet average 2010/km/CH" was adapted to Malaysian conditions, by replacing various processes extracted from MYLCID such as the electricity mix, petrol and diesel. The details inventory information for these datasets that were used for the LCA analysis is provided in the supporting materials at the end of this paper. The aggregated LCIA characterization results are as shown in Table 2 (Onn et al., 2017). The climate change (CO_2 emission) factors obtained for Petrol (2.92 kgCO_2 eq) is about 9% higher than the value (2.67 kgCO_2 eq) reported by the Department of Energy and Climate change. While, the emission factors for electricity (0.82 kgCO_2 eq) is about 10% higher than the values reported by Sustainable Energy Development Authority Malaysia (0.741 kgCO_2 eq) and 25% higher than the values reported by International Energy Agency (0.656 kgCO_2 eq) (Brander et al., 2011; Lorfa et al., 2013; Malaysian Green Technology Corporation, 2012).

2.1. Vehicle emission test cycles

A vehicle emission test cycle is a procedure contained in an emission standard for research and development activities in automobile industry designed to simulate real-life vehicle operation through repeatable sequences and comparable measurement of exhaust emissions for different engines or vehicles under specific conditions. Currently there are more than fifteen vehicle emission test cycle available around the world, where the commonly adopted standards are the Japanese JC08 Cycle, US EPA (SFTP-US06) and European Union's NEDC (New European Driving Cycle). The test cycle used to measure vehicle efficiency will have a significant effect on the resulting energy efficiency values. Selecting the vehicle emission test cycles that reflect global increases in urbanization and congestion is important for representative vehicle comparisons among ICEVs, HEVs and EVs. The US EPA Test cycle and Japanese JC08 were selected in this study, as their testing system includes the effects of urbanization, aggressive driving, ambient temperature, and cabin climate control, as it is necessary to represent real-world driving habits (Pike, 2012).

2.2. ICEVs, HEVs and EVs

At this time, Nissan Leaf and Mitsubishi i-Miev are the only electric vehicles being available in the Malaysian market. In 2012, Nissan Leaf that was introduced to the local market equipped with 24 kW h lithium-ion battery, are able to travel up to

Table 2
Characterization results of the impact of using 1 l of petrol vs. 1 kW h of electricity in Malaysia (Recipe Midpoint (H)).

Impact category	Unit	1 l of petrol	1 kW h of electricity
Climate change	kg CO_2 eq	2.918	0.820
Ozone depletion	kg CFC-11 eq	6.429E−09	4.739E−11
Human toxicity	kg 1,4-DB eq	0.038	0.025
Photochemical oxidant formation	kg NMVOC	0.007	0.003
Particulate matter formation	kg PM10 eq	0.002	0.002
Ionising radiation	kg U235 eq	0.008	1.043E−04
Terrestrial acidification	kg SO_2 eq	0.005	0.004
Freshwater eutrophication	kg P eq	1.268E−05	5.385E−07
Marine eutrophication	kg N eq	1.914E−04	1.100E−04
Terrestrial ecotoxicity	kg 1,4-DB eq	2.414E−04	1.262E−05
Freshwater ecotoxicity	kg 1,4-DB eq	2.931E−04	7.657E−06
Marine ecotoxicity	kg 1,4-DB eq	2.511E−03	1.968E−04
Agricultural land occupation	m^2a	0.001	0.000
Urban land occupation	m^2a	0.002	0.000
Natural land transformation	m^2	2.783E−05	0.000
Water depletion	m^3	0.000	0.014
Metal depletion	kg Fe eq	0.212	0.225
Fossil depletion	kg oil eq	37.171	9.569

Table 3
Characteristics of the selected reference vehicle (Zal, 2014).

Vehicle		Nissan Leaf	Mitsubishi i-Miev	Toyota Camry Hybrid	Toyota Prius Hybrid (3rd Gen)	Toyota Prius C Hybrid	Honda Insight Hybrid	Honda Civic Hybrid	Honda Jazz Hybrid	Honda Jazz petrol	Honda City	Perodua Myvi
Curb weight (kg)		1493	1080	1600	1379	1100	1215	1280	1070	1070	1110	980
Engine displacement				2.5L	1.8L	1.5L	1.3L	1.5L	1.3L	1.5L	1.5L	1.3L
Capacity of battery		24 kW h	16 kW h									
Fuel efficiency (/100 km)	US EPA Test Cycles	21.25 kW h	18.75 kW h	5.88L	4.90L	4.70L	5.74L	5.34L	4.70L	6.53L	–	–
	Japanese JC08	17.00 kW h	11.00 kW h	4.27L	3.29L	2.96L	4.17L	4.31L	3.18L	4.67L	4.59L	5.20L

160 km (100 miles) under US EPA test cycle and 200 km under Japanese JC08 with approximately 34 kW h of electricity. Mitsubishi i-Miev on the other hand, equipped with a 16 kW h lithium-ion battery, consumes approximatively 30 kW h of electricity on 160 km of travel under US EPA test cycle and 110 W h per kilometers under Japanese JC08 (E fuel economy, 2014; United State Environmental Protection Agency, 2014).

Toyota introduced 3 models of hybrid vehicles to the Malaysian market, namely the Toyota Camry Hybrid, Toyota Prius and Toyota Prius C Hybrid. Toyota debuted the third generation Prius to Malaysian market in 2010, Prius C in 2012 and Camry Hybrid (XV50) in 2015. According to the US EPA, the third generation Prius is rated with combined fuel economy of 20.41 km per liter, while, the JC08 rated at 30.4 km per liter and was classified as the most efficient liquid fuel powered car available in the market when it lunched (Reuters, 2015). Under the same US EPA test cycles, the smaller family member of Prius, the Prius C Hybrid is rated with combined fuel economy of 21.26 km per liter and 33.8 km per liter under the JC08. The Toyota Camry Hybrid is the first Toyota hybrid to be assembled in Malaysia. Running with 2.5-l engine, its combined fuel consumption is rated at 17 km per liter under the US EPA test and 23.4 km per liter under the Japanese JC08 (E fuel economy, 2014; United State Environmental Protection Agency, 2014).

In 2010, Honda Malaysia introduced the second generation Honda Insight, which has a fuel efficiency rating of 17.43 km per liter on average according to the US EPA test cycle and 24 km per liter on JC08. Two years later, Honda introduced the Civic Hybrid (third generation) and the Jazz hybrid (2011) into Malaysians market. The Honda Civic Hybrid (third generation) uses similar hybrid system as the Insight model running with 18.71 km per liter of fuel efficiency under EPA test cycle and 23.2 km per liter under the JC08. While, the Honda Jazz hybrid (2011) which is never introduced to the US market due to no business case, didn't have any official EPA testing result. However, US Honda claimed that this model could run with a fuel economy of 21.26 km per liter and the JC08 test cycle shown that it run with a fuel economy of 31.4 km per liter (DeMuro, 2013; E fuel economy, 2014; United State Environmental Protection Agency, 2014; Voelcker, 2013).

The local automaker Perodua produced a B-segment model called Myvi, the Myvi has been the best-selling car in Malaysia for 8 consecutive years, between 2006 and 2013 respectively ("Perodua Myvi XT hits the road," 2014). The Myvi is a rebadged model of the Daihatsu Boon and Toyota Passo, through collaboration of Perodua with both Toyota and Daihatsu. Perodua Myvi offers identical specification and design as the Daihatsu Boon. However, there is no EPA test of this model, as Toyota withdrew the Daihatsu brand from the US market since 1992 (Loveday, 2011). The 1.3-l petrol engine delivers 19.2 km per liter under Japanese JC08. Besides Perodua, Proton which is the Malaysia's first automaker, also offer several models in the same vehicle class segment. However, none of the vehicle models exported to Japan or US market, thus there are no EPA or JC08 test results for comparison.

In the similar vehicle class segment, Honda offers the identical variant of the Jazz family reunion with a conventional internal combustion engine and Honda City which is one of the best-selling models in the non-national segment. The 1.5-l petrol engine version of the Jazz (2015) is rated with 15.31 km per liter of combined fuel economy under the US EPA test and 21.4 km per liter in Japanese JC08. The Honda City (Six Generation) which equipped with 1.5-l petrol engine is rated with fuel economy of 21.8 km per liter in Japanese JC08. Since this model aimed primarily for developing markets, there are no EPA test results for comparison. In the competition of the B-Segment sedans, Toyota offers Vios which equipped with 1.5-l petrol engine as a competitor to Honda City. However, there are no EPA and JC08 test results for Toyota Vios, since it is only produced for Asia Pacific Market (E fuel economy, 2014; Malaysian Automotive Association, 2013; United State Environmental Protection Agency, 2014). The characteristics of the EVs, HEVs, and ICEVs are shown in Table 3.

2.3. Impact assessment

The well-to-wheel analysis were conducted to calculate the potential greenhouse gas (GHG) emission generated by usage of EVs, HEVs and ICEVs in Malaysia. The fuel efficiency data obtained from vehicle emission test cycle were compiled in Table 3. The well-to-wheel analysis was performed using the dataset obtained from Malaysia Life Cycle Inventory Database (MY-LCID) and Ecoinvent 2.2 (Onn et al., 2017). The well-to-wheel analysis revealed that EVs running in the Malaysian electricity mix in the average will produce at least 6.4% to 7.9% more GHG emissions (g CO_2 eq) than HEVs at the same distance. However, they will produced an average of 16–22.5% fewer GHG emissions than the ICEVs. The results are shown in Table 4

Table 4
The Projected GHG emission for each vehicle in per 100 km.

Project	Case Study of EVs vs HEVs vs ICEVs											
Results	Impact assessment											
Method	ReCiPe Midpoint (H) V1.06/World ReCiPe H											
Impact category	Test Cycle	Nissan Leaf	Mitsubishi i-Miev	Toyota Camry Hybrid	Toyota Prius Hybrid	Toyota Prius C Hybrid	Honda Insight Hybrid	Honda Civic Hybrid	Honda Jazz Hybrid	Honda Jazz petrol	Honda City	Perodua Myvi
Global Warming Potential (kg CO_2 eq)	US EPA Test Cycles	17.43	15.38	17.16	14.30	13.71	16.75	15.58	13.71	19.05	–	–
	Japanese JC08	13.94	9.02	12.46	9.60	8.64	12.1	12.58	9.28	13.63	13.39	15.17

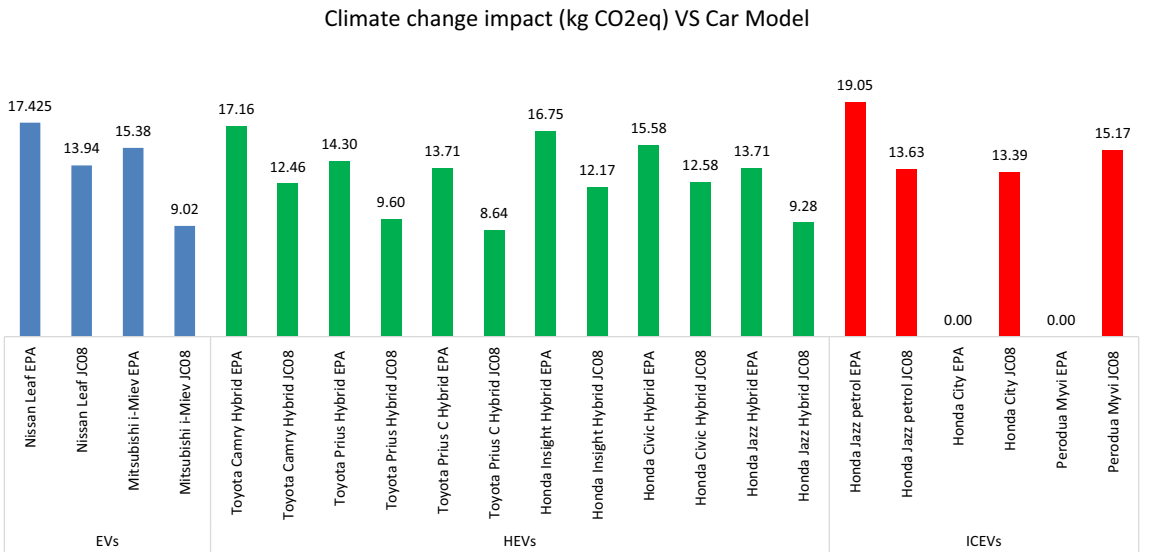

Fig. 1. Climate change impact VS car models per 100 km travel.

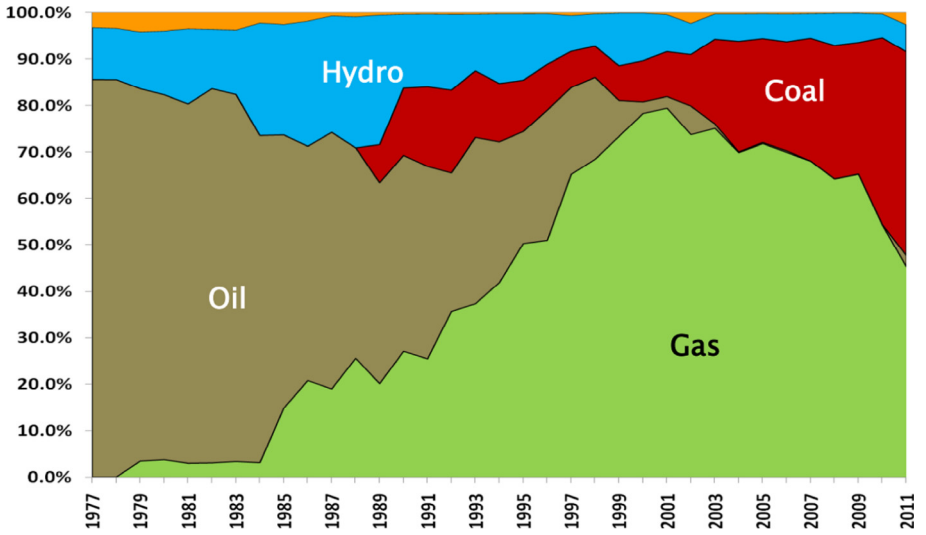

Fig. 2. Evolution of generation mix by fuel type.

and Fig. 1. The Nissan Leaf in all analysis produced more GHG emissions than to all HEVs at the same driving distance. It even performs badly under JC08 test when compared to Honda Jazz Petrol and Honda City Petrol. However, Mitsubishi I-Miev which is the smallest among all models produced remarkably low emissions in JC08 test, outperforming all models except Toyota Prius C. In the EPA test, Mitsubishi I-Miev is producing more GHG emissions than Toyota Prius Hybrid, Toyota Prius C and Honda Jazz Hybrid.

3. Discussion

The use of EVs will results in net CO_2 savings only if they are coupled with the electricity generated to charge the battery has a carbon intensity below 700 g of CO_2 per kilowatt-hour (g CO_2/kW h) (International Energy Agency, 2016) and at least below 760 g of CO_2 per kilowatt-hour based on the impact assessment. It will be a great challenge for Malaysia, as our grid produces 820 g of CO_2 for generation of every kilowatt-hour. Malaysia needs to improve the electricity mix in its power generation. Malaysia is still relying heavily on fossil fuel for power generations, from mainly oil-fired power plant in the pre-1980 to mainly gas-fired power plant in the 2000s and to mainly coal for post-2015 (Fig. 2) (Nor, 2012). The coal-fired power plants demand has doubled from 2005 to 2015 and is going to increase dramatically by another 80% in 2025, which will not

help in the operation of EVs as coal-fired power plants is one of the carbon-intensive power plants that produce an average of 888 g CO_2 eq emission per kW h electricity generation compared to 733 g CO_2eq/kW h for oil-fired power plant and 499 g CO_2eq/kW h for gas-fired power plant (Chong et al., 2015; Gandolphe, 2016; World Nuclear Association, 2010). Thus, in order to harvest the benefit of EVs, massive modernization and transformation should be taken to develop the national grid towards greener sources. Renewable energy was considered as the potential green energy that can be a significant contributor of the country's electricity mix. Countless efforts have been undertaken to encourage the utilization of renewable energy, including biomass, biogas, solar and small hydropower. However, the development of renewable energy in Malaysia is much slower than expected, mainly due to the low cost of coal for energy generation and low energy price in the end-use sector due to high subsidies given by the Malaysian government (Chong et al., 2015; Gandolphe, 2016). Thus, before EVs can be extensively adopted in the local market, issues in the energy sector must be emphasized first, to facilitate a more sustainable electricity generation that could serve as a foundation for EVs adoption.

4. Conclusion

The study indicates that Malaysia as a developing country is not ready for EVs as our electricity generation is still largely dominated by fossil fuels. Based on the well-to-wheel analysis, the GHG emissions produced through the usage of EVs are substantial and it will continue to be so if no change is made to the electricity generation in the near future. Therefore, in order to harvest the benefit of EVs towards climate change and global warming mitigation, massive modernization and transformation should be taken for the development of the national grid towards greener sources.

Alternatively, the introduction of EVs could see as a potential drive for improving and cleaning up the national electricity grid, as well as a catalysis that would create a sustainable long-term solution for the policymaker to easily regulate and optimize the urban transportation system through combining millions of mobile emissions into a few stationary emissions (power plants). These calculations will assist policymakers, automakers, researchers, investors and consumers in assessing the level of GHG emissions produced by different type of vehicles (ICEVs, HEVs and EVs) and also providing a foundation for effective decisions on policies, research and investments in future transport energy.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.trd.2017.06.018.

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